CKM Phase and Spontaneous CP Violation[a]

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Abstract:
The Standard Model for CP violation, the CKM model, works very well in explaining all laboratory experimental data. However, this model does not address the question that where it comes from. The origin of CP violation is still a mystery. In this talk I discuss a model[1] addressing this problem in which the CP violating phase in the CKM matrix is identical to the phase in the Higgs potential resulting from spontaneous CP violation.

Keywords: CP violation, spontaneous symmetry breaking

Since the discovery of parity (P) violation in weak interactions[2] by T.D. Lee and C.-N. Yang in 1956, great progresses have been made in many ways. Parity violation is now understood to be due to $V-A$ current interaction in weak interactions. We have a successful theory for electroweak interactions - the Standard Model (SM)[3]. Tremendous progresses in understanding discrete space-time symmetries, the Parity P, the time reversal T and charge conjugation C, have also been made over the last 50 years or so. In 1964, CP was found to be violated in neutral kaon decays into two and three pions[4]. Since then CP violation have been observed in kaon decay amplitude, and in B meson decays in recent years[5]. Now we have a very successful model for CP violation, the CKM model[6]. T violation has also been established in kaon decays[5]. There is no evidence of violation for the combined symmetry CPT.

It was realized in 1973 by Kobayashi and Maskawa[6] that in the minimal SM if there is a miss-match between weak and mass eigenstates of quarks in the interaction with the weak gauge boson W and Higgs boson, it is possible to have CP violation. In the mass eigenstate basis, the W interaction with quarks can be written as

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{U}\gamma^\mu V_{KM} LDW^+_\mu + h.c.,$$

where V_{KM} is an unitary matrix. It is also called the CKM matrix V_{CKM}. For N generations of quark, V_{CKM} in general has $N(N-1)/2$ mixing physical angles and $(N-1)(N-2)/2$ physical phases. A non-zero value for the sine of the phases lead to CP violation. The minimal number of generations for CP violation is three.

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With three generations of quark, V_{CKM} can be written as

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$
$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}, \quad (1)$$

where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$, and $\gamma = \delta_{13}$. A convenient parametrization used often is the Wolfenstein parametrization[7] with $V_{us} = s_{12}c_{13} = \lambda$, $V_{ub} = s_{13}e^{-i\gamma} = A\lambda^3(\rho - i\eta)$, $V_{cb} = s_{23}c_{13} = A\lambda^2$.

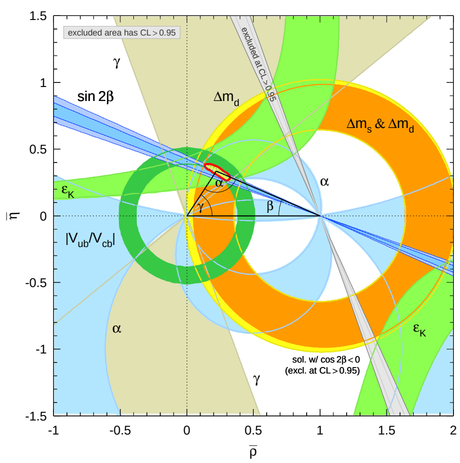

Fig. 1. Constraints on the CKM parameters.

The CKM model is very successful in describing all laboratory experimental results related to CP violation and mixing phenomena. In Fig. 1 we show the current constraints from various experiments[5]. The best fit values and their error bars for the parameters are[5]

$$\lambda = 0.2272 \pm 0.0010\,, \quad A = 0.818^{+0.007}_{-0.017} \quad \rho = 0.221^{+0.064}_{-0.028}\,, \quad \eta = 0.340^{+0.017}_{-0.045}\,.$$

The CKM model although successful, provides no explanation where the CP violating phase comes from which calls for more theoretical studies. There is also hint from matter and anti-matter asymmetry in our universe that there is the need of CP violation beyond the CKM model since it gives too small a value for the observed asymmetry. The origin of CP violation is an outstanding problem of particle physics.

Also in 1973, T. D. Lee[8] proposed that CP violation can come from symmetry breaking in the vacuum, spontaneous CP violation. This provides a understanding of the origin of CP violation. In the minimal SM this is, however, not possible.

With more than one Higgs doublets, it can be realized. For example with two Higgs doublet ϕ_1 and ϕ_2, the most general potential one can write down is given by[8]

$$\begin{aligned}V(\phi) &= -\lambda_1\phi_1^\dagger\phi_1 - \lambda_2\phi_2^\dagger\phi_2 - \lambda_{12}(\phi_1^\dagger\phi_2 + \phi_2^\dagger\phi_1)\\ &+A(\phi_1^\dagger\phi_1)^2 + B(\phi_2^\dagger\phi_2)^2 + C(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \bar{C}(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1)\\ &+\frac{1}{2}[(\phi_1^\dagger\phi_2)(D\phi_1^\dagger\phi_2 + E\phi_1^\dagger\phi_1 + F\phi_2^\dagger\phi_2) + h.c.].\end{aligned}$$

Writing the VEVs as $\langle\phi_1^0\rangle = \rho_1 e^{i\theta}/\sqrt{2}$, $\langle\phi_2^0\rangle = \rho_2/\sqrt{2}$, if $\theta \neq 0$ CP is spontaneously violated. One of the conditions for the Higgs potential to be minimal at the VEV is

$$\left.\frac{\partial V}{\partial\theta}\right|_{min} = (2\lambda_{12} - 4D\cos\theta - E\rho_1^2 - F\rho_2^2)\rho_1\rho_2\sin\theta = 0. \tag{2}$$

This has a non-trivial solution for spontaneous CP violation given by

$$\cos\theta = \frac{1}{4D}(2\lambda_{12} - E\rho_1^2 - F\rho_2^2). \tag{3}$$

The above two Higgs doublet model has complicated interactions with quarks. The Yukawa interactions and mass matrices are given by

$$\begin{aligned}\mathcal{L}_{\phi-q} &= -\bar{Q}_L(\lambda_1^u\phi_1 + \lambda_2^u\phi_2)U_R - \bar{Q}_L(\lambda_1^d\tilde{\phi}_1 + \lambda_2^d\tilde{\phi}_2)D_R,\\ M_u &= \frac{1}{\sqrt{2}}(\lambda_1^u\rho_1 e^{i\theta} + \lambda_2^u\rho_2), \quad M_d = \frac{1}{\sqrt{2}}(\lambda_1^d\rho_1 e^{-i\theta} + \lambda_2^d\rho_2).\end{aligned}$$

Even though $\lambda_{1,2}^{u,d}$ are real, because $M_{u,d}$ are complex one can pbtain a complex V_{CKM}. However in such a model, it is not clear how the spontaneous CP violating phase θ is related to the CKM phase δ_{13}. There are also tree level flavor changing neutral current (FCNC) due to exchange of neutral Higgs,

$$\mathcal{L}_{neutral} = -\frac{1}{\sqrt{2}}[\bar{U}_L\hat{\lambda}_2^u U_R(h_2^0 - \frac{\rho_2}{\rho_1}h_1^0 + i\frac{\rho}{\rho_1}A) + \bar{D}_L\hat{\lambda}_2^d D_R(h_2^0 - \frac{\rho_2}{\rho_1}h_1^0 - i\frac{\rho}{\rho_1}A)],$$

$\rho = \rho_1^2 + \rho_2^2$, The hat indicates $\lambda_2^{u,d}$ are in their mass eigenbasis which are in general complex. Higgs potential will mix the physical Higgs degrees of freedom A and h_i^0.

The model can be made to be consistent with data, but CP violation are very non-CKM like in general, and Higgs masses are constrained to be large due to tree level FCNC. To avoid FCNC at tree level, Weinberg[9] in 1976 proposed to impose additional discrete symmetries such that only one Higgs doublet gives masses to the up and/or down quark sectors. In this case three Higgs doublets are needed to have spontaneous CP violation. In the Weiberg model the CKM matrix is real and in conflict with experimental data[10], in particular with data for $\sin 2\beta_{eff} = 0.678\pm0.032$ from $B \to J\psi K$ decay[5]. In the Weinberg model there is no contribution from CKM sector, and the charged Higgs contribution to $\sin 2\beta_{eff}$ is less than 0.05. The Weinberg model of spontaneous CP violation is decisively ruled out by CP violation in $B \to J/\psi K$.

In the following we present a model[1] where the CP violating phase in the CKM matrix has a clear relation with the spontaneous CP violating phase in the Higgs potential by identifying these two phases to be the same up to a sign.

We start the discussion by showing that the above idea is indeed realizable. Let us consider the following Yukawa couplings with multi-Higgs doublets,

$$L_Y = \bar{Q}_L(\Gamma_{u1}\phi_1 + \Gamma_{u2}\phi_2)U_R + \bar{Q}_L\Gamma_d\tilde{\phi}_d D_R + h.c.\ , \tag{4}$$

$\tilde{\phi}_d = -i\sigma_2\phi_d^*$ and ϕ_d may be one of the $\phi_{1,2}$ or another doublet Higgs field. The Yukawa couplings $\Gamma_{u1,u2,d}$ must be real if CP is only violated spontaneously.

The Higgs doublets when expressed in terms of the component fields and their VEV v_i are given by

$$\phi_i = e^{i\theta_i}H_i = e^{i\theta_i}\begin{pmatrix} \frac{1}{\sqrt{2}}(v_i + R_i + iA_i) \\ h_i^- \end{pmatrix}. \tag{5}$$

The quark mass terms in the Lagrangian are

$$L_m = -\bar{U}_L\left[M_{u1}e^{i\theta_1} + M_{u2}e^{i\theta_2}\right]U_R - \bar{D}_L M_d e^{-i\theta_d}D_R + h.c.\ , \tag{6}$$

where $M_{ui} = -\Gamma_{ui}v_i/\sqrt{2}$.

The phases θ_1 and θ_d can be absorbed by redefining the fields U_R and D_R. However, the phase difference $\delta = \theta_2 - \theta_1$ cannot be removed and it depends on the Higgs potential. A non-zero δ indicates spontaneous CP violation. Without loss of generality, we work in the basis where D_L, D_R are already in their mass eigenstates. In this basis the down quark mass matrix M_d is diagonalized, which will be indicated by $\hat{M}_d$. In general the up quark mass matrix $M_u = M_{u1} + e^{i\delta}M_{u2}$ is not diagonal. Diagonalizing M_u produces the CKM mixing matrix. One can write $\hat{M}_u = V_{CKM}M_uV_R^\dagger$. V_R is an unknown unitary matrix. A direct identification of the phase δ with the phase δ_{13} in the CKM matrix is not possible in general. There are, however, classes of mass matrices which allow such a connection. A simple example is provided by setting V_R to be the unit matrix. With this condition, $M_u = V_{CKM}^\dagger\hat{M}_u$. One then needs to show that $V_{CKM}^\dagger$ can be written as

$$V_{CKM}^\dagger = (M_{u1} + e^{i\delta}M_{u2})\hat{M}_u^{-1}. \tag{7}$$

Expressing the CKM matrix in this form is very suggestive. If V_{CKM} can always be written as a sum of two terms with a relative phase, then the phase in the CKM matrix can be identified with the phase δ.

We now demonstrate that it is the case by using the parametrization in Eq. (1) as an example. To get as close as to the form in Eq. (7), we write the CKM matrix eq. (1) as[5]

$$V_{CKM} = \begin{pmatrix} e^{-i\delta_{13}} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} c_{12}c_{13}e^{i\delta_{13}} & s_{12}c_{13}e^{i\delta_{13}} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}.$$

Absorbing the left matrix into the definition of U_L field, we have

$$M_{u1} = \begin{pmatrix} 0 & -s_{12}c_{23} & s_{12}s_{23} \\ 0 & c_{12}c_{23} & -c_{12}s_{23} \\ s_{13} & s_{23}c_{13} & c_{23}c_{13} \end{pmatrix} \hat{M}_u \ ,$$
$$M_{u2} = \begin{pmatrix} c_{12}c_{13} & -c_{12}s_{23}s_{13} & -c_{12}c_{23}s_{13} \\ s_{12}c_{13} & -s_{12}s_{23}s_{13} & -s_{12}c_{23}s_{13} \\ 0 & 0 & 0 \end{pmatrix} \hat{M}_u \ , \tag{8}$$

and $\delta = -\delta_{13}$. We therefore find that it is possible to identify the CKM phase with that resulting from spontaneous CP violation. Note that as long as the phase δ is not zero, CP violation will show up in the charged currents mediated by W exchange. The effects do not disappear even when Higgs boson masses are all set to be much higher than the W scale. Furthermore, $M_{1,2}$ are fixed in terms of the CKM matrix elements and the quark masses, as opposed to being arbitrary in general multi-Higgs models.

We comment that the solution is not unique even when V_R is set to be the unit matrix[1]. One can easily verify this by taking another parametrization for the CKM matrix, such as the original Kobayashi-Maskawa (KM) matrix[6]. More physical requirements are needed to uniquely determine the connection. The key point we would like to emphasis is that there are solutions where the phase in the CKM matrix can be identified with the phase causing spontaneous CP violation in the Higgs potential.

The mass matrices M_{u1} and M_{u2} can be written in a more elegant way with

$$M_{u1} = V^\dagger_{CKM}\hat{M}_u - \frac{e^{i\delta}}{\sin\delta} Im(V^\dagger_{CKM})\hat{M}_u \ ,$$
$$M_{u2} = \frac{1}{\sin\delta} Im(V^\dagger_{CKM})\hat{M}_u \ . \tag{9}$$

Alternatively, a model can be constructed with two Higgs doublets couple to the down sector and one Higgs doublet couples to the up sector[1]. We will concentrate on the above scenario for detailed discussions. In the following we go further to construct a realistic model.

A common problem for models with spontaneous CP violation is that a strong QCD θ term will be generated[11]. Constraint from neutron dipole moment measurement will rule out spontaneous CP violation as the sole source if there is no mechanism to make sure that the θ term is small enough. The model mentioned above faces the same problem. We therefore supplement the model with a Peccei-Quinn (PQ) symmetry[12] to ensure a small θ.

To have spontaneous CP violation and also PQ symmetry simultaneously, more than two Higgs doublets are needed[13]. For our purpose we find that in order to have spontaneous CP violation with PQ symmetry at least three Higgs doublets $\phi_i = e^{i\theta_i}H_i$ and one complex Higgs singlet $\tilde{S} = e^{i\theta_s}S = e^{i\theta_s}(v_s + R_s + iA_s)/\sqrt{2}$ are required. The Higgs singlet with a large VEV renders the axion from PQ symmetry

breaking to be invisible[14,15], thus satisfying experimental constraints on axion couplings to fermions. We will henceforth work with models with an invisible axion[14] with PQ charges for various fields given by

$$Q_L : 0\ ,\ \ U_R : -1\ ,\ \ D_R : -1\ ,\ \ \phi_{1,2} : +1\ ,\ \ \phi_d = \phi_3 : -1\ ,\ \ \tilde{S} : +2\ .$$

The Higgs potential is

$$\begin{aligned}
V = &-m_1^2 H_1^\dagger H_1 - m_2^2 H_2^\dagger H_2 - m_3^2 H_3^\dagger H_3 - m_{12}^2 (H_1^\dagger H_2 e^{i(\theta_2-\theta_1)} + h.c.) - m_s^2 S^\dagger S\\
&+ \lambda_1 (H_1^\dagger H_1)^2 + \lambda_2 (H_2^\dagger H_2)^2 + \lambda_t (H_3^\dagger H_3)^2 + \lambda_s (S^\dagger S)^2\\
&+ \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_3' (H_1^\dagger H_1)(H_3^\dagger H_3) + \lambda_3'' (H_2^\dagger H_2)(H_3^\dagger H_3)\\
&+ \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \lambda_4' (H_1^\dagger H_3)(H_3^\dagger H_1) + \lambda_4'' (H_2^\dagger H_3)(H_3^\dagger H_2)\\
&+ \frac{1}{2}\lambda_5 ((H_1^\dagger H_2)^2 e^{i2(\theta_2-\theta_1)} + h.c.) + \lambda_6 (H_1^\dagger H_1)(H_1^\dagger H_2 e^{i(\theta_2-\theta_1)} + h.c.)\\
&+ \lambda_7 (H_2^\dagger H_2)(H_1^\dagger H_2 e^{i(\theta_2-\theta_1)} + h.c.) + \lambda_8 (H_3^\dagger H_3)(H_1^\dagger H_2 e^{i(\theta_2-\theta_1)} + h.c.)\\
&+ f_1 H_1^\dagger H_1 S^\dagger S + f_2 H_2^\dagger H_2 S^\dagger S + f_3 H_3^\dagger H_3 S^\dagger S\\
&+ d_{12} (H_1^\dagger H_2 e^{i(\theta_2-\theta_1)} + H_2^\dagger H_1 e^{-i(\theta_2-\theta_1)}) S^\dagger S\\
&+ f_{13} (H_1^\dagger H_3 S e^{i(\theta_3+\theta_s-\theta_1)} + h.c.) + f_{23} (H_2^\dagger H_3 S e^{i(\theta_3+\theta_s-\theta_2)} + h.c.)\ . \qquad (10)
\end{aligned}$$

Note that only two independent phases occur in the above expression, which we choose to be $\delta = \theta_2 - \theta_1$ and $\delta_s = \theta_3 + \theta_s - \theta_2$. The phase $\theta_3 + \theta_s - \theta_1$ can be written as $\delta + \delta_s$. Differentiating with respect to δ_s to get one of the conditions for minimization of the potential, we get

$$f_{13} v_1 v_3 v_s \sin(\delta_s + \delta) + f_{23} v_2 v_3 v_s \sin\delta_s = 0\ . \qquad (11)$$

It is clear that δ and δ_s are related with

$$\tan\delta_s = -\frac{f_{13} v_1 \sin\delta}{f_{23} v_2 + f_{13} v_1 \cos\delta}\ . \qquad (12)$$

The phase δ is the only independent phase in the Higgs potential. A non-zero $\sin\delta$ is the source of spontaneous CP violation and also the only source of CP violation in the model.

Removing the would-be Goldstaone bosons, one can write the Yukawa interactions for physical Higgs degrees of freedom as the following[1]

$$\begin{aligned}
L_Y = &\bar{U}_L [\hat{M}_u \frac{v_1}{v_{12} v_2} - (\hat{M}_u - V_{CKM} Im(V_{CKM}^\dagger) \hat{M}_u \frac{e^{i\delta}}{\sin\delta}) \frac{v_{12}}{v_1 v_2}] U_R (H_1^0 + i a_1^0)\\
&+ \bar{U}_L \hat{M}_u U_R [\frac{v_3}{v_{12} v}(H_2^0 + i a_2) - \frac{1}{v} H_3^0 + \frac{v_3^2}{v^2 v_s}(H_4^0 + i a)]\\
&- \bar{D}_L \hat{M}_d D_R [\frac{v_{12}}{v_3 v}(H_2^0 - i a_2) + \frac{1}{v} H_3^0 + \frac{v_{12}^2}{v^2 v_s}(H_4^0 - i a)]\\
&+ \sqrt{2} \bar{D}_L [V_{CKM}^\dagger \hat{M}_u \frac{v_1}{v_2 v_{12}} - (V_{CKM}^\dagger \hat{M}_u - Im(V_{CKM}^\dagger) \hat{M}_u \frac{e^{i\delta}}{\sin\delta})\ \frac{v_{12}}{v_1 v_2}] U_R H_1^-\\
&- \sqrt{2} \frac{v_3}{v_{12} v} \bar{D}_L V_{CKM}^\dagger \hat{M}_u U_R H_2^- - \sqrt{2} \frac{v_{12}}{v v_3} \bar{U}_L V_{CKM} \hat{M}_d D_R H_2^+ + h.c.\ . \qquad (13)
\end{aligned}$$

Here a is the axion. The fields, H_i^0 and a_i^0 are not the mass eigenstates yet and will be mixied in the potential.

Note that the couplings of a and H_4^0 to quarks are suppressed by $1/v_s$, and that only the exchange of H_1^0 and a_1^0 can induce tree level FCNC interactions. The FCNC coupling is proportional to $V_{CKM}Im(V^\dagger_{CKM})\hat{M}_u$.

For the model presented here, FCNC only involves the up quark sector. The most stringent constraint on the Higgs mass comes from $D^0 - \bar{D}^0$. We find that the Higgs mass can be as low as a hundred GeV from this constraint. Such low Higgs mass can be probed at LHC and ILC.

The neutron EDM d_n provides much information on the model parameters. The standard model predicts a very small[16] d_n ($< 10^{-31}e$ cm). The present experimental upper bound on neutron EDM d_n is very tight[5]: $|d_n| < 0.63 \times 10^{-25}e$ cm. In the model considered above, the quark EDMs will be generated at loop levels due to mixing between a_i and H_i.

The one loop contributions to the neutron EDM are suppressed for the usual reason of being proportional to light quarks masses to the third power for diagram in which the internal quark is the same as the external quark. In our model, there is a potentially large contribution when there is a top quark in the loop. However, the couplings to top are proportional to s_{13}, therefore the contribution to neutron EDM is much smaller than the present upper bound. It is well known that exchange of Higgs at the two loop level may be more important than the one loop contribution, through the quark EDM, quark color EDM, and the gluon color EDM. We find that in the model discussed above, the neutron EDM can reach the present experimental bound. Improved measurement on neutron EDM can provide us with more information.

To summarize, I have described a model in which the CP violating phase in the CKM mixing matrix to be the same as that causing spontaneous CP violation in the Higgs potential. When the Higgs boson masses are set to be very large, the phase in the CKM matrix can be made finite and CP violating effects will not disappear. An interesting feature of this model is that the FCNC Yukawa couplings are fixed in terms of the quark masses and CKM mixing angles, making phenomenological analysis much easier.

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